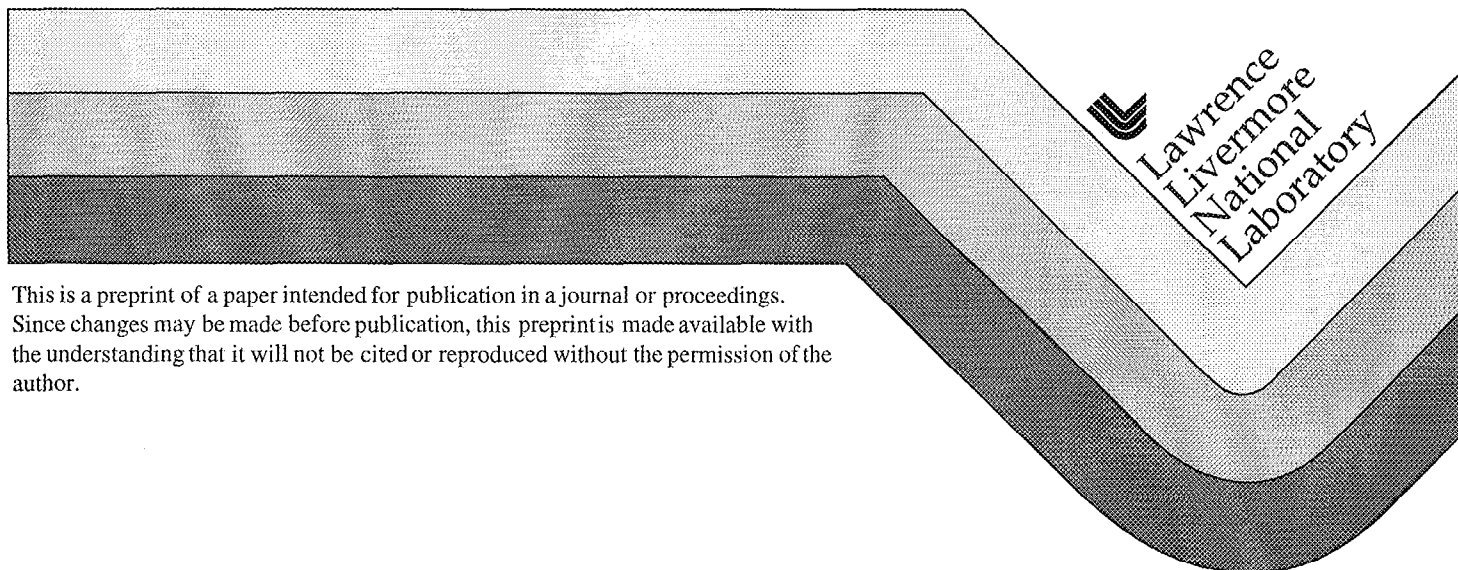


# Error Analysis for Fast Scintillator-Based ICF Burn History Measurements

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### **Abstract**

Plastic scintillator material acts as a neutron-to-light converter in instruments that make ICF burn history measurements. Light output for a detected neutron has a fast rise time ( $<20$  ps) and a relatively long decay constant (1.2 ns). For a burst of neutrons whose duration is much shorter than the decay constant, instantaneous light output is approximately proportional to the integral of the neutron interaction rate with the scintillator material. Burn history is obtained by deconvolving the exponential decay from the recorded signal. The error in estimating signal amplitude for these integral measurements is calculated and compared with a direct measurement in which light output is linearly proportional to the interaction rate.

## I. INTRODUCTION

A fast 25-ps resolution neutron detector has been developed for ICF burn history measurements.<sup>1</sup> It is based on the fast rise time of a conventional plastic scintillator. Neutron kinetic energy is transferred to the scintillator primarily by elastic collisions with hydrogen atoms. The resulting recoil protons quickly slow down via coulomb collisions, transferring their energy to electrons which excite light-emitting luminescent states in the scintillator. In BC-422 scintillator material, the light output distribution for a neutron collision exhibits a fast ( $< 20$  ps) rise time and a characteristic 1.2-ns decay constant.

The temporal distribution for light produced when a burst of neutrons excite the scintillator is the convolution of the neutron temporal distribution with the characteristic scintillator response. If the duration of the neutron burst is much shorter than the decay rate of the scintillator, then information about the neutron temporal distribution is contained entirely in the leading edge of the output pulse. The temporal distribution of neutrons exciting the scintillator can be recovered from a measured signal by deconvolving the effect of the scintillator response. For short excitation times, this is approximately the derivative of the recorded signal.

A measurement such as this, where the recorded signal represents the integral of the desired quantity, can have

somewhat poorer statistics than a direct measurement detecting the same number of events. An integral measurement is often perceived to be inferior to a direct recording of the desired signal. A common belief is that differentiation is an inherently noisy process. Also, in contrast with direct recording methods, signal details for an integral measurement cannot be seen without first going through a decoding process. In this paper, measurement errors associated with direct and integral measurements are evaluated and compared. It is not differentiation that adds extra noise to the fast detector signal, but rather the statistics associated with the formation of the signal. Understanding the source of measurement error is essential for using the detector properly and interpreting measurement results.

## II. MEASUREMENT ERROR

As outlined in Fig. 1, an isotropic point source emits monoenergetic neutrons with a temporal distribution  $f(t)$ . Some of these neutrons enter and interact with a neutron-to-light converter to produce light. A portion of this light is collected and recorded by a fast light-sensitive detector. Additionally, to restrict the following discussion to a comparison of integral and direct measurements, the following assumptions are made: the neutron transit time across the converter is negligible, each detected neutron produces the same amount of

light, and the light detector is much faster than the temporal resolution of interest.

Two types of neutron-to-light converters are considered: direct and integral. A direct converter emits light at a rate linearly proportional to the neutron interaction rate with the converter. Light is emitted at the instant of an interaction. An integral converter, on the other hand, emits light at a rate linearly proportional to the integral of the number of interactions. The standard deviation associated with each type of measurement of  $f(t)$  will be discussed and compared.

### A. Direct Measurements

For this discussion, a direct measurement is defined as one in which the detector system response  $\Delta t_{\text{det}}$  is much shorter than the temporal width  $\Delta t_i$  of the distribution to be measured. Let  $k_{\text{dir}}$  represent the fraction of source neutrons that interact with the converter and  $\eta$  represent the fraction of neutrons interacting with the converter that are detected by the light detector. Under the condition  $k_{\text{dir}}\eta \ll 1$  the detector statistics may be treated as Gaussian. Then the number of events  $N_i$  detected during a time interval  $\Delta t$  about a time  $t_i$  may be written as

$$N_i = k_{\text{dir}}\eta \int_{t_i - \frac{\Delta t}{2}}^{t_i + \frac{\Delta t}{2}} f(t) dt . \quad (1)$$

The error  $\sigma_{N_i}$  in determining the number of events in a time interval is given by standard counting statistics as

$$\sigma_{N_i} = \sqrt{N_i}. \quad (2)$$

## B. Integral Measurements

An integral measurement is defined as one in which each detected event causes light to be emitted at a constant rate for a time period much greater than the width of the distribution  $f(t)$  being measured. To allow easy comparison of the integral measurement technique to the direct measurement technique,  $k_{\text{int}}$  for the integral measurement is defined to be the fraction of source neutrons that interact with the converter. Additionally,  $\eta$  is defined as the fraction of neutrons interacting in the converter that produce detected light during a resolution time  $\Delta t$ . Furthermore, it is require that  $\eta \ll 1$ .

For an integral measurement, the recorded signal  $m(t)$  is proportional to the integral of the distribution function, that is

$$m(t) = k_{\text{int}} \eta \int_0^t f(t') dt', \quad (3)$$

and its error is given by

$$\sigma_{m(t)} = \sqrt{m(t)}. \quad (4)$$

The number of detected events  $N_i$  in the time interval  $\Delta t$  about time  $t_i$  is given by

$$N_i = k_{\text{int}} \eta \int_{t_i - \frac{\Delta t}{2}}^{t_i + \frac{\Delta t}{2}} f(t) dt = m(t_i + \frac{\Delta t}{2}) - m(t_i - \frac{\Delta t}{2}). \quad (5)$$

If the light coupling efficiency between the neutron-to-light converter and the light detector is weak ( $\eta \ll 1$ ), then only a fraction of the detected events produce detected light during a resolution time period  $\Delta t$ . Under weak coupling, the measured values for  $m(t)$  in separate temporal resolution elements are essentially independent measurements. Under these conditions the standard deviation is that for the difference of two independent measurements: one at the beginning and one at the end of the time interval of interest. Thus,

$$\sigma_{N_i} = \left[ m(t_i + \frac{\Delta t}{2}) + m(t_i - \frac{\Delta t}{2}) \right]^{\frac{1}{2}} = \left[ N_i + 2m(t_i - \frac{\Delta t}{2}) \right]^{\frac{1}{2}}. \quad (6)$$

### III. DISCUSSION AND EXAMPLE

A comparison of Eq. 6 with Eq. 2 shows that the error for an integral measurement is always greater than the error for an equivalent direct measurement detecting the same number of events. The amount of degradation depends on the integral of the distribution function up to the time interval of interest.

For times late in the distribution, the error in  $N_i$  is determined by the integral of the number of counts,  $m(t_i - \Delta t/2)$ , and is nearly independent of the number of counts in the time interval  $\Delta t$ .

There is a useful tradeoff between measurement accuracy and temporal resolution which is best observed when data are presented as a histogram of counts per time bin versus time. This format is convenient for attaching statistically based error bars. The relative error for a measurement is given by  $\sigma_{N_i}/N_i$ . At times late in the measured distribution, the relative error is approximately  $[2m(t - \Delta t/2)]^{1/2}/N_i$ , where  $m(t)$  is a slowly varying function of time and  $N_i$  is proportional to the bin width  $\Delta t$ . Thus, simply increasing the bin width produces a proportional reduction in measurement error. A factor of two increase in bin width doubles the counts in the bin and reduces the relative measurement error by a factor of 2.

Figure 2 shows the application of error bars to a 120-ps FWHM Gaussian temporal distribution containing 2500 events. The two upper plots show the data binned with  $\Delta t = 7.5$  ps, and the two lower plots have  $\Delta t = 15$  ps. Plots in the left column have direct measurement statistics applied; plots in the right column have integral measurement statistics. For the integral measurements, the continual increase in error with time is clearly noted, as is the proportional reduction in relative error with increased bin width.

The error calculation for an integral measurement presented in this paper is a worst case estimate. It assumes that a measurement for  $m(t)$  at time  $t_1$  is independent of the measurement at time  $t_2$ . This is an accurate description for the statistics of the fast scintillator-based neutron detector currently used for measuring the reaction-rate history of an ICF target. The integral measurement technique has allowed the exploitation of the fast rise-time feature of a relatively slow detector impulse response to produce a 5× speed enhancement and a 100× sensitivity improvement over the previously used detector.<sup>2</sup>

## ACKNOWLEDGMENT

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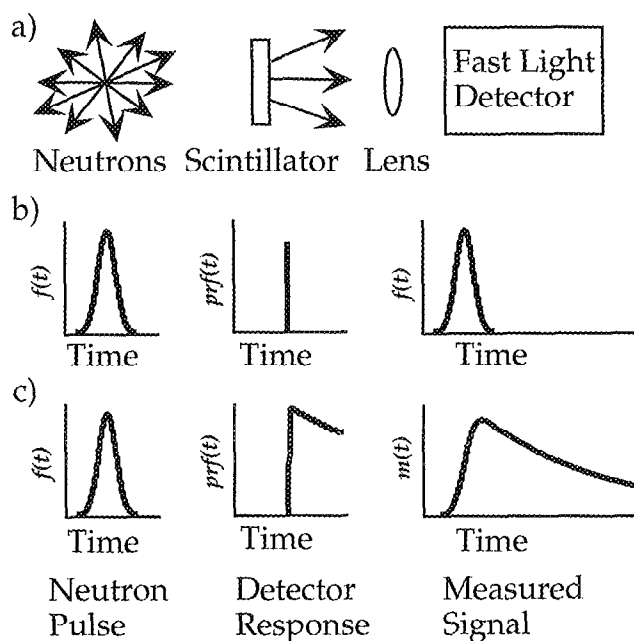


FIG. 1. Detector geometry and temporal signals. (a) Detector geometry showing neutron source, neutron-to-light converter, and light detector. (b) and (c) show the temporal pulse of source neutrons, the detector impulse response ( $prf$ ), and finally the signal measured by the fast light detector for both a direct measurement (b) and an integral measurement (c).

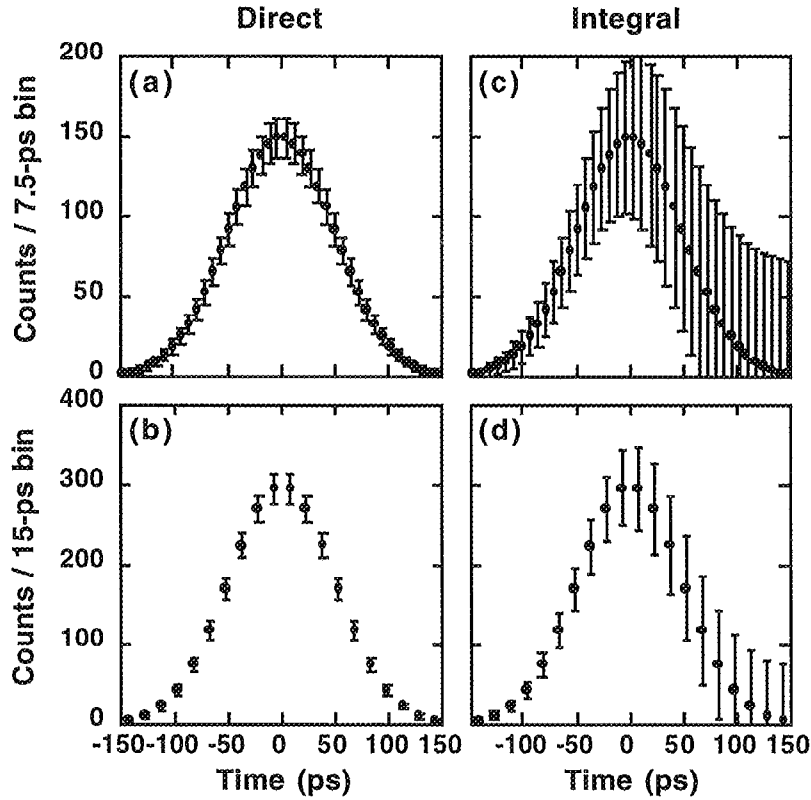


FIG. 2. A 120-ps FWHM Gaussian distribution containing 2500 events shown with error bars. (a) and (b) are distributions for direct measurements where standard counting statistics apply, (c) and (d) are for integral measurements. Time bins in (b) and (d) are twice as wide as those in (a) and (c). Note that  $\sigma_N/N$  for integral measurements decreases by a factor of 2 (not the  $\sqrt{2}$ ) with the coarser binning.